Booster Subharmonic RF Capture Design

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1.0 Motivation and Requirements

Successful operation of the APS storage ring (SR) in top-off mode requires a reliable injector system that efficiently delivers up to 10 nC of charge at 7 GeV to the SR. One way to possibly improve injector reliability is to inject the linac beam directly into the booster and bypass the PAR. Direct injection into the booster imposes several requirements on the booster rf system. First, the rf must capture the complete linac beam or at least a large fraction of it. Second, bunch purity must be preserved. Third, the whole acceleration process from injection to extraction at 7 GeV must be as efficient (as measured by particle loss) as possible at up to 10 nC of extracted charge. Finally, the rf system parameters should be chosen to preserve the present linear ramp profile used in the booster (0.325 to 7 GeV in 223 ms). The last requirement minimizes the required recommissiong effort since the magnet ramps are left unchanged.

These requirements can be achieved by adding a subharmonic rf system at the appropriate frequency and gap voltage in the booster. The subharmonic system in combination with the present booster 352-MHz rf system act together to accelerate the beam to 7 GeV while minimizing beam loss and preserving bunch purity. The central problem of this design is to determine the proper subharmonic and 352-MHz rf system parameters to satisfy these requirements. The acceleration and capture process is achieved by using the subharmonic system to capture the linac macropulse and at about 3 GeV turning on the 352-MHz system to quickly capture and accelerate the beam to 7 GeV. The subharmonic system will also support future booster upgrades such as stacking at low energy for more uniform top-up and lifetime adjustment flexibility for stored beam operation.

2.0 Choice of Subharmonic RF Frequency

The choice of subharmonic frequency is driven by the linac rf thermionic gun macropulse length. The rf thermionic guns have nominal pulse lengths of 40 ns (gun 1) and 10 ns (gun 2). The subharmonic period sets the maximum macropulse length that can be captured in a stationary bucket. This maximum length is further reduced by a factor for nonstationary buckets [1]. For the booster, the beam is injected into an accelerating bucket so the achievable linac macropulse length that can be captured by the booster is approximately 30 - 50% less than the subharmonic period. One therefore expects some beam to be lost at injection into the booster for linac macropulse length greater than or equal to the subharmonic period.

To capture the complete macropulse for both guns would require a < (1 / 40 ns) = 25 MHz subharmonic frequency. Due to the difficulty of building high-voltage low-frequency rf cavities, this requirement can be relaxed so that at least the 10-ns pulse from gun 2 can be captured. If gun 1 is to be used for injection, bunch cleaning can be employed at low energy before the 352-MHz system is powered or the gun 1 macropulse length must be reduced. Bunch cleaning will be much easier due to the large subharmonic bucket spacing compared to the spacing for 352-MHz buckets (2.84ns) . Finally, the subharmonic frequency must be an integer subharmonic of 352 MHz (h = 432). Table 1 lists the subharmonic frequencies considered in this study. All four frequencies can completely capture the macropulse generated by gun 2. The exact choice of subharmonic frequency can be made based on rf considerations such as ease of construction and maximum gap voltage obtainable.

TABLE 1. Subharmonic frequencies used in the simulation study

Frequency (MHz)	Subharmonic Period (ns)	Subharmonic Number	Total Booster Buckets
29.327	34.10	12	36
39.103	25.57	9	48
43.991	22.73	8	54
58.655	17.05	6	72

3.0 Choice of Subharmonic Gap Voltage

The subharmonic gap voltage required depends on the linac macropulse length and the bunch length required to efficiently capture and accelerate the beam by the 352-MHz rf system. The linac macropulse must be damped to < 2.84 ns before it can be captured and accelerated by the 352-MHz rf system. Unfortunately radiation damping is very small up to about 3 GeV where the damping time is 17.2 ms (at the injection energy of 0.325 GeV the damping time is 13.5 seconds). For energies less than approximately 3 GeV, adiabatic damping of the energy spread is the dominant mechanism for reducing the bunch length since the bunch length is (nearly) proportional to the energy spread [1,2]. The proportionality is not exact since it is scaled by the synchrotron frequency, which does change somewhat as the synchronous phase and energy changes.

For initial bunch lengths on the order of 20 ns the beam must be accelerated using the subharmonic system to at least 3.25 GeV, which would result in an energy spread 10 times smaller than that at injection (0.325 GeV). The gap voltage needs to be large enough to provide an adequate over voltage factor at 3.25 GeV to compensate for radiation loss (296.7 keV/turn) as well as beam loading. This requires a subharmonic gap voltage of somewhere around 400 to 600 kV (depending on choice of frequency) to insure adequate overvoltage. The exact value of the gap voltage is explored via simulation described in the next section.

4.0 Subharmonic Gap Voltage Determined by `Elegant` Tracking Simulation

`Elegant[3]`tracking simulations were performed to determine the gap voltage required for each frequency listed in Table 1 to capture and bunch the linac macropulse to < 2.84 ns. The initial linac macropulse length was varied depending on the subharmonic frequency and the energy spread was taken to be +/- 1% (hard edge full width) at 325 MeV. These initial beam parameters resulted in ~0.5% particle losses at injection. The simulation used 35,000 particles to estimate the worst-case capture efficiency as well as bunch purity during capture and acceleration. Beam loading was simulated for the subharmonic cavity by using the standard resonator impedance model with Q = 40,000 and Rs = 5 MΩ. Finally, `elegant` has the capability to simulate radiation damping and quantum excitation, and these effects were included in the simulations.

Each simulation was done using two subharmonic cavities. The first cavity, called the capture cavity, was powered at a constant level at low voltage to capture the beam with minimum loss. Then an identical cavity (called the ramped cavity) with the same subharmonic frequency was turned on and ramped to full power until the bunch length achieved was < 2.84 ns. The simulation could have been done using a single ramped subharmonic cavity. Separating the cavities into one constantly powered and one ramped allowed easier optimization of the injection and final gap voltage in the simulations.

Using a gap voltage of 200 kV for the capture cavity and optimizing the linac macropulse length for each subharmonic frequency simulated resulted in ~0.5% particle losses at injection. The ramped cavity was turned on in 10 ms and in phase with the capture cavity when the synchronous phase (as determined by the capture cavity alone) reached 121.8 degrees (overvoltage factor of 1.176), which is at approximately 2.53 GeV for the momentum ramp rate of 29.9 MeV/ms. The 352-MHz system was turned on at approximately 3 GeV for each subharmonic frequency studied. The exact 352-MHz turn-on time depended on when the bunch length was compressed sufficiently, which differed slightly for each subharmonic frequency. Single cavities were used to minimize computation time even though an actual system would need to have multiple cavities to achieve the total gap voltage required [4, 5].

TABLE 2. Subharmonic capture simulation results for various subharmonic frequencies

Frequency (MHz)	Subharmonic Number	Total Subharmonic Gap Voltage (kV)	Initial Bunch Length (ns)	Minimum Bunch Length (ns)
29.327	12	650	15.36	2.44
39.103	9	500	12.94	2.57
43.991	8	450	11.44	2.57
58.655	6	400	8.40	2.33

Table 2 summarizes the total gap voltage required for each subharmonic cavity frequency (both capture and ramped) to achieve a 2.3- to 2.5-ns full-width bunch length (defined as the difference between arrival time of the leading and trailing particles in the bunch). Table 2 and Table 1 clearly show the tradeoffs involved in the choice of subharmonic frequency. One would like to use the lowest frequency possible to capture the longest possible linac pulse. A lower subharmonic frequency would require much more gap voltage to achieve the bunch length required for efficient 352-MHz capture. In general it is more difficult to design low-frequency cavities with high gap voltage (> 200 kV) because of voltage breakdown [4, 5]. Next we explore a way to reduce the required total gap voltage yet still use a low-frequency cavity for capture of a long linac macropulse.

5.0 Simulations Using Two Subharmonic Cavities with Different Frequencies

Table 2 illustrates the tradeoff between subharmonic frequency and gap voltage. This is understood simply: the bunching required is inversely proportional to the time derivative of gap voltage, which is the product of the subharmonic frequency and peak gap voltage in the frequency domain [1]. One can increase the effective gap voltage time derivative by using a combination of low-frequency subharmonic cavity and high-frequency subharmonic cavity (both cavity frequencies need to be harmonically related to each other as well as to 352 MHz). This has the effect of reducing the total gap voltage required for a given desired final bunch length (~2.5 ns for efficient capture by the 352-MHz booster rf system).

The subharmonic frequencies chosen for this study were the 12th subharmonic (29.327 MHz) previously described and the 3rd subharmonic (117.310 MHz) of 352 MHz. The 12th subharmonic was kept powered at a constant 200 kV thoughout the ramp and the 3rd subharmonic was ramped (linearly) to 250 kV in 10 ms to capture and bunch the beam when the beam energy reached approximately 2.40 GeV. After the beam was captured and compressed by the subharmonic cavities to <~ 2.5 ns (which occurred at a beam energy of approximately 3.16 GeV), the primary 352-MHz system was turned on and ramped to full power. The same cavity mode parameters were used for the 3rd and 12th subharmonic cavities as before, and the design parameters Q = 40,000 and Rs = 221 MΩ were used for the quality factor and total shunt impedance of the four 352-MHz booster cavities.

Figure 1 shows the results of the simulation where 110,000 particles were used. The figure shows the beam captured and accelerated to 7 GeV by both subharmonic and 352-MHz systems without particle loss. The full-width bunch length plotted shows a transient at injection due to longitudinal phase-space missmatch where the initial momentum spread of the beam was +/- 1%. Particle losses at injection were about 0.5% due to the missmatch. The 352-MHz sytem ramp profile was chosen to be a two-term fourth-order polynomial (linear and quartic terms used), which guarantees a near linear ramp for approximately 50 ms after system turn-on. The full power level of the 352-MHz system is 10 MV.

The most critical point where particle loss occurs is when the 352-MHz system is turned on. Eight simulations were performed where the phase of the 352-MHz system was varied which showed that particle loss starts to occur when the phase differs by more than +/- 1 degree from nominal. The phase tolerance for the 117-MHz system at turn on was found to be somewhat more relaxed at +/- 5 degrees from nominal. A crucial design issue for the 352-MHz system will be how to achieve +/- 1 degree phase stability at system turn on.

6.0 Conclusion

The studies presented here indicate that a subharmonic system optimized using both 3rd and 12th subharmonic cavities (117.3 and 29.3 MHz) provides the minimum total gap voltage required to capture and accelerate a 15-ns linac macropulse at up to10 nC with +/- 1% energy spread. The simulations also show particle losses less than a part in 110,000 when including radiation damping, quantum excitation, and rf cavity beam loading. The only particle losses were found to be at injection due to phase-space mismatch. Optimization of the subharmonic capture idea requires knowledge of the gap voltage that can be achieved with an actual cavity. In general the lower the cavity frequency the harder it is to engineer a cavity that can sustain a given gap voltage without breakdown. Phase and amplitude control of both subharmonic and 352-MHz systems also needs to be carefully considered so that bunch purity is preserved and operational flexibility maintained. Phase stability is particularly important for the high power 352-MHz system, which preliminary simulation studies show needs 1 degree regulation at turn-on. Future optimization studies need to include amplitude stability tolerance studies for each ramped rf system at turn on.

Other tradeoffs can be explored such as using 9th and 3rd (39.1 and 117.3 MHz) subharmonic cavities. Using cavities with frequencies higher than 39.1 MHz is not practical due to the short linac macropulses that can be captured. Recent simulations using a more realistic linac energy spread of +/- 0.25% will allow the 12th subharmonic cavity gap voltage to be lowered to 150 kV while keeping injection particle loss < 1%. The simulations use 300 kV for the 117-MHz system for complete capture and acceleration by the 352-MHz rf system and show 1 part in 110,000 bunch purity. The modest gap voltage increase required in the 117-MHz system should not be a problem since its frequency is much higher than the 12th subharmonic gap voltage.

7.0 Acknowledgements

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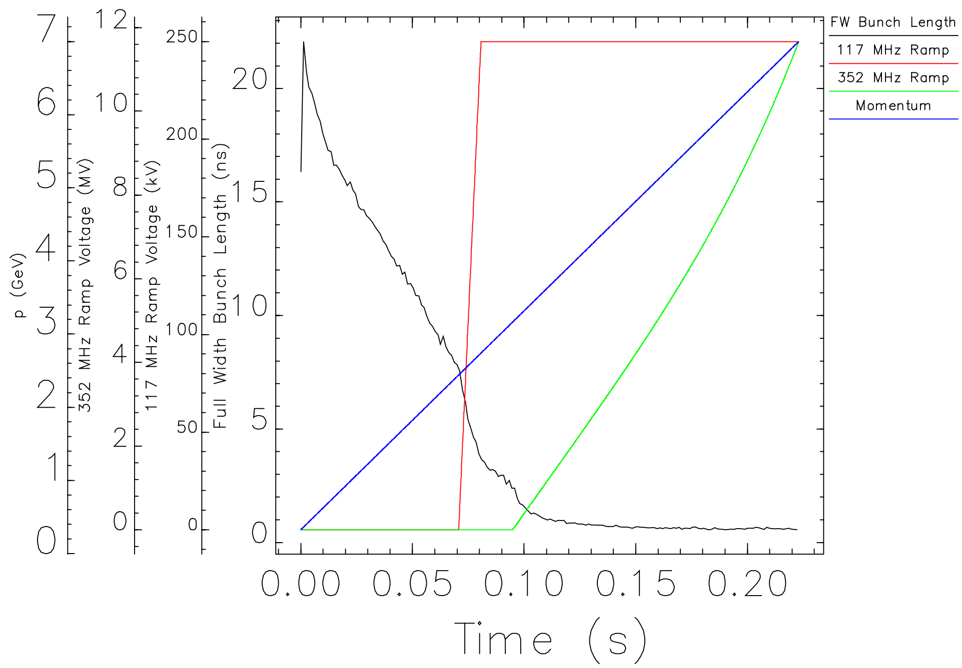
FIGURE 1. Full-width bunch length, 117-MHz, 352-MHz voltage ramps and momentum vs time with the 29.3-MHz capture cavity at 200 kV constant gap voltage



8.0 References

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